DECLARATION

I, the undersigned, of 2-12, Nakazaki 2-chome, Kita-ku, Osaka, Japan, hereby certify that I am well acquainted with the English and Japanese languages, that I am an experienced translator for patent matter, and that the attached document is a true English translation of

Japanese Patent Application No. 10-038758

that was filed in Japanese.

I declare that all statements made herein of may own knowledge are true, that all statements on information and belief are believed to be true, and that these statements were made with the knowledge that willful statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Signature:

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[Name of the Document] SPECIFICATION

[Title of the Invention] BIPOLAR TRANSISTOR

[Claims]

[Claim 1] A bipolar transistor comprising an emitter layer, a base layer and a collector layer, characterised by having

a multi-quantum barrier portion being provided in a region of the emitter layer in proximity to the base layer and composed of a plurality of barrier layers and well layers alternately stacked to perform the function of reflecting an incident wave of carriers in the emitter layer injected from the base layer and provide such a phase that the incident wave of carriers and a reflected wave of carriers intensify each other.

[Claim 2] The bipolar transistor according to claim 1, characterised in that

the barrier layers and well layers of the multi-quantum barrier portion are composed of respective semiconductor materials having different band gaps.

[Claim 3] The bipolar transistor according to claim 1 or 2, characterised in that

a conduction band in the emitter layer containing the multi-quantum barrier portion has a band discontinuity value of substantially zero.

[Claim 4] The bipolar transistor according to any one of claims 1 to 3, characterised in that

the base layer is strained.

[Claim 5] The bipolar transistor according to any one of claims 1 to 4, characterised in that

the emitter layer and the base layer are composed of respective semiconductor materials having different band gaps, and

a band gap between a valence band and a conduction band in the base layer grades decreasingly from a region of the base layer closer to the emitter layer toward a region of the base layer closer to the collector layer.

[Claim 6] The bipolar transistor according to any one of claims 1 to 5, characterised in that

the base layer is composed of a semiconductor containing at least silicon and germanium.

[Claim 7] The bipolar transistor according to claim 6, characterised in that

the multi-quantum barrier portion has a superlattice structure composed of a $Si_{1-x}Ge_x/Si$ multiple layer.

[Claim 8] The bipolar transistor according to claim 6, characterised in that

the multi-quantum barrier portion has a superlattice structure composed of a $Si_{1-x-y}Ge_xC_y/Si$ multiple layer.

[Claim 9] The bipolar transistor according to any one of claims 1 to 8, characterised in that

the multi-quantum barrier portion is disposed in a region of the emitter layer exterior to a depletion region formed between the emitter layer and the base layer at a maximum design voltage when the transistor is operating.

[Claim 10] The bipolar transistor according to claim 9, characterised in that

the barrier layer at the end of the multi-quantum barrier portion closer to the base layer is disposed in such a position as to prevent the tunnelling of the carriers from the depletion region formed between the emitter layer and the base layer to the well layer adjacent to the barrier layer at the end of the multi-quantum barrier portion closer to the base layer.

[Detailed Description of the Invention]

[Technical Field to which the Invention Belongs]

The present invention relates to a bipolar transistor and particularly relates to the bipolar transistor having an increased current amplification factor by suppressing reverse injection of carriers from a base.

[Prior Art]

Because of its excellent RF characteristics, a bipolar transistor has conventionally been used as an active device operable in the microwave/milliwave bands. In particular, most vigorous research and development has been directed to a heterojunction bipolar transistor (HBT) using a III-V compound semiconductor such as GaAs. In recent years, attention has been focused on a HBT using a SiGe material, which is a IV-IV compound material that can be fabricated on a low-cost silicon substrate.

The representative structures for implementing higher-speed SiGe HBTs are the following two types of HBTs: i.e., a HBT which comprises a collector layer of Si, a base layer of SiGe, and an emitter layer of Si and in which a Ge composition ratio in the SiGe base layer is increased gradually from a region in contact with the Si emitter layer toward a region in contact with the Si

collector layer to provide a graded composition base layer (L. Harame et al., "Optimization of SiGe HBT Technology for High Speed Analog and Mixed-Signal Applications," IEDM Tech. Dig. 1993, p.71); and a HBT which comprises a collector layer of Si, a base layer of SiGe, and an emitter layer of Si and in which the SiGe base layer has an extremely reduced thickness, an increased Ge composition ratio, and an increased doping concentration to provide a uniform composition base layer (A. Schuppen et al., "Enhanced SiGe Heterojunction Bipolar Transistors with 160 GHz-fmax," IEDM Tech. Dig. 1995, p.743.).

Figure 8 is a band diagram of the former heterojunction bipolar transistor having the graded composition base layer out of the two types of HBTs. As can be seen from the band state shown in the drawing, an electric field induced by the graded composition causes carriers injected into the SiGe base layer to drift in the SiGe base layer toward the collector layer. Since the travelling of the carriers caused by the drift electric field is at a higher speed than the travelling thereof caused by diffusion, a base transit time is reduced and excellent RF characteristics are obtained.

Figure 9 is a band diagram of the latter heterojunction bipolar transistor having the uniform composition base structure out of the two types of HBTs. As can be seen from the band state shown in the drawing, the base layer is extremely thinned to reduce the base transit time and provide excellent RF characteristics. In this case, the thinning of the base layer incurs the risk of increasing the base resistance, and therefore the base layer is

doped with a high-concentration impurity to lower the base resistance. In addition, SiGe having a high Ge composition ratio is used in the base layer to prevent reverse injection of carriers from the base layer doped with the high-concentration impurity into the emitter, so that a heterojunction barrier formed between the SiGe base layer and the Si emitter layer is increased. In this case also, excellent RF characteristics are obtained. In particular, the concentration of carriers in the base layer is increased to reduce the base resistance and thereby increase a maximum oscillation frequency.

[Problems that the Invention is to solve]

In the conventional HBT using the graded composition base shown in Figure 8, however, it is required to increase the gradient of the composition ratio in order to increase the intensity of the drift electric field induced by the graded composition. In short, it is required to reduce the Ge composition ratio in a region of the base layer closer to the emitter layer and raise the Ge composition ratio in a region of the base layer closer to the collector layer. To satisfy the requirement, the region of the base layer closer to the emitter layer normally has a Si composition without containing Ge. In this case, the base/emitter PN junction forms a silicon/silicon homojunction. In increasing the maximum oscillation frequency f_{max} of the HBT, it is effective to reduce the base resistance as represented by the following equation (1). If a base doping concentration is increased to reduce the base resistance, however, the quantity of holes injected from the base layer into the emitter layer is naturally increased.

In the case where the emitter/base junction forms a homojunction or where the emitter/base junction forms a heterojunction but has a nearly Si composition at the end of the base, the quantity of carriers reversely injected into the emitter is increased because the base layer has no heterojunction barrier or, if any, an extremely low heterojunction barrier. Accordingly, the current amplification factor β is not increased.

[Equation 1]

$$f_{\max} = \sqrt{\frac{f_T}{8\pi \cdot R_B \cdot C_{BC}}}$$

f_T: current gain cutoff frequency

R_B: base resistance

C_{BC}: base/collector junction capacitance

The fact that the current amplification factor β is not increased can also be derived from the relationship represented by the following equation (2), which is established among the current amplification factor β, the band discontinuity value ΔEv of a valence band at the emitter/base junction, and a doping concentration N_B in the base layer.

[Equation 2]

$$\beta = \frac{J_n}{J_p} = \left(\frac{N_E}{N_B}\right) \cdot \left(\frac{V_n}{V_p}\right) \cdot exp\left(\frac{\Delta E_V}{kT}\right)$$

N_E: doping concentration in emitter layer

N_B: doping concentration in base layer

V_n: speed of electron diffusion in base layer

V_p: speed of hole diffusion in emitter layer

k: Boltzmann's constant

T: absolute temperature

In the case of using such a graded composition base, it becomes therefore possible to reduce the base transit time and improve the current gain cutoff frequency f_T. However, the increase of the maximum oscillation frequency f_{max} cannot eventually be expected since the concentration of carriers in the base layer cannot be increased.

On the other hand, the conventional structure using the uniform composition base shown in Figure 9 can suppress reverse injection of carriers from the base layer because a high heterojunction barrier is formed between the SiGe base layer having a high Ge composition ratio and a Si emitter layer. If the doping concentration in the SiGe base layer is to be further increased in order to increase the maximum oscillation frequency f_{max}, as described above, the quantity of carriers reversely injected is increased. To prevent this, it is required to further enhance the height of the heterojunction barrier by further increasing the Ge composition ratio in the SiGe base layer, which increases the difference in lattice constant between the emitter layer and the base layer. As a result, a critical film thickness at which a dislocation occurs in the base layer presents a problem.

Therefore, there is a limit to the improvement of the RF characteristics of a bipolar transistor which is accomplished by providing a heterojunction in the emitter/base junction and

enhancing the function of suppressing reverse injection of carriers from the base into the emitter through the formation of a heterojunction barrier.

The present invention has been made in view of the foregoing problems, and therefore has its object of providing a bipolar transistor wherein a current amplification factor is increased and restrictions on the increase of the base doping concentration are relaxed with the provision of a region having the function of suppressing reverse injection of carriers from the base layer into the emitter layer irrespective of a barrier formed at the emitter/base junction and wherein the current amplification factor can be improved even when a base doping concentration is increased to increase the maximum oscillation frequency f_{max} by relaxing the restrictions on the increase of the base doping concentration.

[Means for Solving the Problems]

To solve the above problems, in the present invention, a multi-quantum barrier (MQB), composed of a superlattice structure consisting of two types of extremely thin films having different compositions and alternately stacked, is provided in a region of the emitter adjacent the emitter/base junction. The MQB reflects a wave of carriers reversely injected from the base, which fact is used to effectively increase the height of a heterojunction barrier (barrier height) and thereby suppress the reverse injection of the carriers from the base layer.

As described as a basic structure in Claim 1, the bipolar transistor according to the present invention comprises an emitter layer, a base layer and a collector layer, and has a multi-quantum

barrier portion being provided in a region of the emitter layer in proximity to the base layer and composed of a plurality of barrier layers and well layers alternately stacked to perform the function of reflecting an incident wave of carriers in the emitter layer injected from the base layer and provide such a phase that the incident wave of carriers and a reflected wave of carriers intensify each other.

With the arrangement, not only a barrier induced by the discontinued valence band at the emitter/base junction but also the multi-quantum barrier portion prevents reverse injection of carriers from the base layer into the base layer. Since the reverse injection of carriers is suppressed, it becomes possible to increase the current amplification factor while improving RF characteristics such as a maximum oscillation frequency f_{max} even if the doping concentration of carriers in the base layer is increased.

As described in claim 2, in the bipolar transistor, the barrier layers and well layers of the multi-quantum barrier portion are preferably composed of respective semiconductor materials having different band gaps.

This facilitates the implementation of a multi-quantum barrier layer having the function of suppressing reverse injection of carriers.

As described in claim 3, in the bipolar transistor, a conduction band in the emitter layer containing the multi-quantum barrier portion preferably has a band discontinuity value of substantially zero.

This provides a band structure presenting no obstacle to the movement of majority carriers in the emitter layer, which enhances the effect of improving a current amplification factor.

As described in claim 4, in the bipolar transistor, the base layer is preferably strained.

With this arrangement, a particularly high effect is achieved when the difference in lattice constant between the emitter layer and the base layer is large.

As described in claim 5, in the bipolar transistor, the emitter layer and the base layer are preferably composed of respective semiconductor materials having different band gaps, and a band gap between a valence band and a conduction band in the base layer preferably grades decreasingly from a region of the base layer closer to the emitter layer toward a region of the base layer closer to the collector layer.

With this arrangement, the travelling speed of carriers in the base layer is determined by a drift velocity, not by a diffusion speed, so that the base transit time is reduced and a current gain cutoff frequency f_T is increased. In addition, the multi-quantum barrier portion suppresses reverse junction of carriers from the base layer into the emitter layer irrespective of the band discontinuity value reduced by the provision of the graded composition base. Moreover, reduction in base resistance attributable to higher-concentration base doping or increase in thickness of the base layer can also be achieved, which increases a maximum oscillation frequency f_{max}.

As described in claim 6, in the bipolar transistor, the base

layer is preferably composed of a semiconductor containing at least silicon and germanium.

With this arrangement, a heterojunction bipolar transistor excellent in RF characteristics can be obtained while using inexpensive semiconductor materials.

In this heterojunction bipolar transistor, the multi-quantum barrier portion may have a superlattice structure composed of a $Si_{1-x}Ge_x/Si$ multiple layer as described in claim 7, or may have a superlattice structure composed of a $Si_{1-x-y}Ge_xC_y/Si$ multiple layer as described in claim 8.

By composing the multi-quantum barrier portion of a superlattice structure of a $Si_{1-x-y}Ge_xC_y/Si$ multiple layer, the critical film thickness of the $Si_{1-x-y}Ge_xC_y$ layer at the multi-quantum barrier portion is particularly increased, so that it becomes possible to further increase the effective barrier height of the multi-quantum barrier portion without incurring a dislocation.

As described in claim 9, in the bipolar transistor, the multi-quantum barrier portion is preferably disposed in a region of the emitter layer exterior to a depletion region formed between the emitter layer and the base layer at a maximum design voltage when the transistor is operating.

With this arrangement, the function of suppressing reverse injection of carriers from the base into the emitter can maximally be performed in any operating condition.

In this case, as described in claim 10, the barrier layer at the end of the multi-quantum barrier portion closer to the base layer is preferably disposed in such a position as to prevent the

tunnelling of the carriers from the depletion region formed between the emitter layer and the base layer to the well layer adjacent to the barrier layer at the end of the multi-quantum barrier portion closer to the base layer.

With this arrangement, such an improvement in RF characteristics as described above can be expected without degrading the function of suppressing reverse injection of carriers performed by the multi-quantum barrier portion.

[Embodiment of the Invention]

The present embodiment relates to a heterojunction bipolar transistor characterised by having a multi-quantum barrier, composed of a superlattice structure consisting of two types of extremely thin films having different compositions and alternately stacked, in a region of the emitter adjacent the emitter/base junction and by effectively increasing the height of a heterojunction barrier (barrier height) through the effect of reflecting carriers thereby suppressing reverse injection of the carriers from the base layer. The heterojunction bipolar transistor is directed to the improvement in current gain and RF characteristics.

Figure 1 shows the structure of an NPN heterojunction bipolar transistor having a multi-quantum barrier composed of a Si/SiGe superlattice provided in the emitter layer according to the present embodiment. As shown in the drawing, a high-concentration n-type Si subcollector layer 2, an n-type Si collector layer 3, a high-concentration p-type SiGe base layer 4, an n-type Si emitter layer 5 and a high-concentration n-type Si emitter contact layer

6 are stacked sequentially on a Si substrate 1 by a UHV-CVD method. A collector electrode 20, a base electrode 21, and an emitter electrode 22 are disposed on the Si subcollector layer 2, the SiGe base layer 4, and the Si emitter contact layer 6, respectively.

A MQB layer 10 as a multi-quantum barrier portion having a superlattice structure composed of extremely thin Si and SiGe layers that have been alternately stacked is provided in a region of the Si emitter layer 5 adjacent the emitter/base junction portion. The MQB layer 10 has such a structure that the compositions and film thicknesses thereof have been adjusted to reflect a wave of holes reversely injected from the SiGe base layer 4 into the Si emitter layer 5 and provide a phase in which the incident wave of holes and a reflected wave of holes intensify each other. Specifically, the MQB layer 10 has a multilayer structure consisting of well layers 10a each composed of a SiGe layer with a thickness of L_1 and barrier layers 10b each composed of a Si layer with a thickness of L_2. The respective thicknesses and compositions of the well layers 10a and barrier layers 10b are determined to satisfy the relationship represented by the following equation (3).

[Equation 3]

$$\frac{\sqrt{2m_1 * E}}{h} \cdot L_1 = \frac{2m-1}{4}$$

$$\frac{\sqrt{2m_2 * (E - \Delta Ev)}}{h} \cdot L_2 = \frac{2n-1}{4}$$

m_1*: effective mass of holes in SiGe layer (well layer)

m_2*: effective mass of holes in Si layer (barrier layer)

L_1: thickness of SiGe layer (well layer)

L_2: thickness of Si layer (barrier layer)

E: energy of incident holes

ΔEv: valence band discontinuity value at Si/SiGe heterojunction

h: Planck's constant

m, n: integers

Specifically, the MQB layer 10 according to the present embodiment is composed of a superlattice layer consisting of five pairs of the barrier layers 10b each formed of Si having a thickness of 1.4 nm and the well layers 10a each formed of $Si_{0.7}Ge_{0.3}$ having a thickness of 1.4 nm. In this case, the MQB increases an effective barrier height by approximately 150 meV.

On the other hand, the SiGe base layer 4 has a graded composition base structure in which a Ge composition ratio increases substantially continually from 0% to 20% from a region closer to the Si emitter layer 5 toward a region closer to the Si collector layer 3.

Figure 2 is a band diagram of the NPN heterojunction bipolar transistor having the multi-quantum barrier composed of the Si/SiGe superlattice and provided in the Si emitter layer 5 according to the present embodiment. As shown in the drawing, the multi-quantum barrier consisting of the five pairs of Si barrier layers 10b and $Si_{0.7}Ge_{0.3}$ well layers 10a is provided in the region of the Si emitter layer 5 adjacent the emitter/base junction. This enhances the effective barrier height sensed by the holes from the SiGe base layer 4 by approximately 150 meV. The enhanced effective barrier height suppresses reverse injection of the holes into the Si emitter layer 5 even when a hole concentration in the SiGe base layer 4 is increased, and thereby provides a sufficient current gain. As a result, there can be implemented a HBT having an extremely high maximum oscillation frequency f_{max}.

Figure 3 shows a model for calculating a barrier height ΔUe enhanced by the MQB layer 10 according to the present invention. The enhanced barrier height ΔUe in each of the five pairs of Si/SiGe superlattice structures composing the MQB layer 10 was calculated for the three structures of $Si/Si_{0.2}Ge_{0.8}$, $Si/Si_{0.3}Ge_{0.7}$ and $Si/Si_{0.4}Ge_{0.6}$. At this time, the respective band discontinuity values ΔEv of the valence bands at the individual heterojunctions between the well layers 10a and the barrier layers 10b are 150 meV, 225 meV and 300 meV. As shown in drawing, the barrier height ΔUe enhanced by the MQB layer 10 is represented at a height virtually formed downward from the valence band of the barrier layer 10b. It is to be noted that the energy level Ec of a conduction band in the whole Si emitter layer 5 including the MQB layer 10 is

substantially flat and the band discontinuity value in the whole Si emitter layer 5 including the MQB layer 10 is substantially zero.

Figure 4 shows the result of calculating the barrier heights ΔUe enhanced by the MQB layer 10 by varying the number of the atomic monolayers of well layers 10a and barrier layers 10b. The calculations were performed by varying x to 0.2, 0.3 and 0.4 in $Si_{1-x}Ge_x$ representing SiGe composing the well layers 10a, i.e., for the three structures of $Si/Si_{0.2}Ge_{0.8}$, $Si/Si_{0.3}Ge_{0.7}$ and $Si/Si_{0.4}Ge_{0.6}$. In the drawing, the abscissa axis represents a well/barrier thickness expressed in the number of atomic monolayers (one atomic monolayer corresponds to (5.43/4) Å). As shown in the drawing, the enhanced barrier height ΔUe in the MQB layer 10 tends to decrease with an increase in the number of monolayers in any of the cases where x is varied to 0.2, 0.3 and 0.4. The maximum value of the enhanced barrier height ΔUe increases with an increase in Ge composition ratio to reach approximately 240 meV when each of Si and $Si_{0.4}Ge_{0.6}$ of $Si/Si_{0.4}Ge_{0.6}$ is composed of 8 atomic monolayers. When the effective barrier height in the MQB layer 10 is increased by about 240 meV, the function of suppressing reverse injection of holes from the SiGe base layer 4 into the Si emitter layer 5 is performed particularly remarkably. Even if there are slight fluctuations in the film thicknesses and compositions of the MQB layer 10, the function of suppressing reverse injection of holes mentioned above will easily be performed provided that the effective barrier height ΔUe in the MQB layer 10 is on the order of 100 meV.

When the barrier height ΔUe is excessively increased in the case where SiGe is used in the well layers 10a of the MQB layer 10, it is necessary to further increase the Ge composition ratio in the well layers 10a. However, the increased Ge composition ratio may cause a dislocation depending on the critical film thickness of SiGe. The respective critical film thicknesses for $Si_{0.2}Ge_{0.8}$, $Si_{0.3}Ge_{0.7}$ and $Si_{0.4}Ge_{0.6}$ when the underlie is Si are approximately 180 nm, 56 nm and 25 nm.

In increasing the critical film thickness, it is effective to use $Si_{1-x-y}Ge_xC_y$ and Si to compose the well layers 10a and barrier layers 10b of the MQB layer 10, respectively. By adjusting the Ge composition to 40% or more and adding a slight amount of C (on the order of several percentage) thereto, a strained lattice can be alleviated without greatly varying the magnitude of the band discontinuity value ΔEv at the emitter/base junction, which increases the critical film thickness of the well layer 10a. By thus composing the MQB layer 10 of $Si_{1-x-y}Ge_xC_y$/Si, a larger band discontinuity value ΔEv can be obtained without exceeding the critical film thickness, which effectively suppresses reverse injection of holes from the SiGe base layer 4 into the emitter layer 5.

Next, a description will be given to the effect of improving the RF characteristics of the HBT in which the effective barrier height ΔUe has been enhanced with the provision of the MQB layer 10 in the Si emitter layer 5.

Figure 5 shows the result of calculating the degree to which the base transit time τ_B of carriers has been reduced (base transit

time reduction factor) in the HBT in which the barrier height ΔUe has been enhanced by the MQB layer 10 and the Ge composition ratio in the SiGe base layer 4 has been graded as shown in Figure 2, compared with the base transit time in the conventional HBT using the uniform composition base layer. As is represented by the following equations, the base transit time τ_B is a factor directly influencing the current gain cutoff frequency f_T, which is higher as the base transit time τ_B is shorter.

$$f_T = 1/(2\pi \cdot \tau_{EC})$$

$$\tau_{EC} = \tau_E + \tau_{EB} + \tau_B + \tau_{BC} + \tau_C$$

where τ_{EC} is the emitter-to-collector transit time of carriers; τ_E is a time required for the accumulation of minority carriers reversely injected into the emitter; τ_{EB} is a charge/discharge time for C_{EB}; τ_B is the transit time of majority carriers in the base; τ_{BC} is a charge/discharge time for C_{BC}; and τ_C is the transit time of electrons in the collector.

In the case of using the uniform composition base layer, however, τ_B is determined by a diffusion speed as represented by the following equation.

$$\tau_B = W_B^2/(2k \cdot T \cdot \mu e/q)$$

where W_B is the thickness of the base layer; μe is the mobility of electrons; and T is a temperature.

In the case of using the graded composition base layer, on the other hand, τ_B is determined by a drift velocity as represented by the following equations.

$$\tau_B = W_B / (\mu e \cdot E)$$

$$E = \Delta E_{gr} / q \cdot W_B$$

As will be seen from Figure 5, the base transit time is reduced in accordance with the gradient if a graded composition is given to the base layer having the same thickness as the conventional uniform composition base layer. When the gradient of the band gap is 300 meV in the graded composition, the base transit time is reduced to approximately 20% of the base transit time in the uniform composition base.

Figure 6 shows the result of calculating the degree to which the maximum oscillation frequency f_{max} (f_{max} increase factor) has been increased in the HBT in which the barrier height ΔUe has been enhanced with the provision of the MQB layer 10 and the graded composition base layer having an increased thickness for a reduced base resistance R_B is provided, compared with the maximum oscillation frequency f_{max} in the conventional HBT having the heavily doped uniform composition base layer. It is to be noted that the film thickness of the SiGe base layer has been adjusted to provide a base transit time equal to the base transit time in the heavily doped uniform composition base layer of the conventional HBT. Since the base transit time is reduced by using the graded composition base layer, as shown in the drawing, the thickness of the base layer can be increased as the base gap gradient resulting from the graded composition is increased. As a result, the base resistance R_B is reduced and the maximum oscillation frequency f_{max} is increased. As shown in the drawing, the maximum oscillation

frequency f_{max} when the band gap gradient resulting from the graded composition is 300 meV is more than 1.5 times higher than the maximum oscillation frequency in the uniform composition base.

In the HBT according to the present embodiment, therefore, the following effects can be derived from the RF characteristics shown in Figure 6 and 5.

First, the provision of the MQB layer 10 having the barrier height ΔUe in the Si emitter layer 5 achieves the same effect as achieved when the band discontinuity value ΔEv of the valence band at the emitter/base junction is substantially increased (see the equation (2)), resulting in an improved current amplification factor β. In other words, the provision of the MQB layer 10 for suppressing reverse injection of holes from the SiGe base layer 4 into the Si emitter layer 5 reduces the current J_p shown in the equation (2) flowing from the base to the emitter and thereby improves the current amplification factor β. The effect is achievable whether the emitter/base junction is a heterojunction or not. Consequently, the same effect can also be achieved in a normal bipolar transistor other than a HBT.

Second, since the graded composition has been given to the SiGe base layer 4 and the MQB layer 10 is provided in the Si emitter layer 5, the Ge composition ratio in the SiGe base layer 4 varies such that the band gap in the SiGe base layer 4 gradually decreases from the region of the SiGe base layer 4 closer to the Si emitter layer 5 toward the region thereof closer to the Si collector layer 3, whereby the current gain cutoff frequency f_T is increased. As stated previously, if the base doping concentration is increased

to lower the resistance of the uniform composition base layer in the conventional HBT, the quantity of holes reversely injected is increased so that a sufficient current gain is not obtained. By contrast, since the effective barrier height is enhanced with the provision of the MQB layer 10 in the HBT according to the present invention, the effective barrier height is held sufficiently large even when the band discontinuity value of the heterojunction at the emitter/base junction is reduced with the provision of the graded composition base and the base doping concentration is increased, which suppresses reverse injection of holes. Hence, there can be obtained the heavily doped base layer having a graded composition, which has conventionally been unobtainable. As a result, the base transit time of electrons is reduced and the RF characteristics are improved.

Thirdly, since the base transit time is reduced by providing the graded composition base layer, the thickness of the base layer can be increased with the increasing band gap gradient resulting from the graded composition. As a result, the base resistance is reduced and the maximum oscillation frequency f_{max} is increased.

Fourthly, a sufficient current gain obtainable with a low Ge composition ratio achieves the effect of suppressing the occurrence of a dislocation due to a thermal budget during the subsequent process step, which presents a problem when a high Ge composition ratio is used, i.e., the effect of increasing the thermal budget. Briefly, this achieves the effect of providing the device fabrication process with an increased margin as well as increased device reliability.

Fifthly, the temperature characteristics of the bipolar transistor can also be improved. Specifically, since the distribution of hole concentrations in the valence band of the SiGe layer 4 shifts downwardly at an increased temperature, as shown in Figure 7(a), the current amplification factor β of the bipolar transistor exhibits a general tendency to lower as the temperature T increases, as represented by the lines 11 and 12 in Figure 7(b). The tendency is particularly conspicuous when the band discontinuity value ΔEv is low. By contrast, the bipolar transistor according to the present invention provides a high current amplification factor β even at a high temperature owing to the function of suppressing reverse injection of holes performed by the MQB layer 10, as represented by the line 13 in Figure 7(b).

Thus, by providing the MQB layer 10 in the region of the emitter layer 5 adjacent the emitter/base junction of the heterojunction bipolar transistor, the current gain and RF characteristics of the heterojunction bipolar transistor can be improved.

For the MQB layer 10 to reliably perform the barrier function, the whole MQB layer 10 is preferably disposed externally of a depletion region formed between the emitter and the base at a maximum design voltage (region depleted when a maximum design voltage is applied between the emitter and the base). This is because, if the MQB layer 10 has a part located within the depletion region, the function of suppressing reverse injection of holes may not be performed reliably with respect to the part. In addition, the barrier layer 10b of the MQB layer 10 which is adjacent to the

SiGe base layer 4 is preferably placed in such a position as to prevent the tunnelling of holes from the depletion region to the well layer 10a which is adjacent to the barrier layer 10b, since the occurrence of the tunnelling degrades the function of suppressing reverse injection of holes. Preferably, the MQB layer 10 in the Si emitter layer 5 is at a distance shorter than the diffusion length of holes from the SiGe base layer 4.

Although the present embodiment has described the improved characteristics of the heterojunction bipolar transistor as a single element, it will easily be appreciated that the HBT according to the present invention may also be used for the bipolar part of a BiCMOS device in which the bipolar transistor and a CMOS have been integrated.

Although the present embodiment has described the NPN SiGe HBT by way of example, it will easily be appreciated that the present invention is also applicable to a PNP bipolar transistor. Alternatively, the present invention may also be applied to a normal homojunction bipolar transistor other than the HBT and to a heterojunction bipolar transistor of III-V compound semiconductor layers, as stated previously.

[Effects of the Invention]

According to the present invention, a multi-quantum barrier (MQB), composed of a superlattice structure consisting of two types of extremely thin films having different compositions and alternately stacked, is provided in a region of the emitter adjacent the emitter/base junction, and effectively increase the height of a heterojunction barrier (barrier height) by using the effect

of reflecting carriers. Accordingly, reverse injection of the carriers from the base layer is suppressed, which increases the current amplification factor β. In addition, since the structural restrictions of the base layer are relaxed, the current gain cutoff frequency f_T and the maximum oscillation frequency f_{max} can be improved.

[Brief Description of the Drawings]

[Fig. 1]

A cross-sectional view of an NPN heterojunction bipolar transistor according to an embodiment, in which a MQB layer as a Si/SiGe multi-quantum barrier portion is provided in an emitter layer.

[Fig. 2]

A band diagram of the NPN heterojunction bipolar transistor according to the embodiment, in which the MQB layer as the Si/SiGe multi-quantum barrier portion is provided in the emitter layer.

[Fig. 3]

A band diagram showing a model for calculating a barrier height ΔUe enhanced by the MQB layer in the transistor of the embodiment.

[Fig. 4]

A graph showing the result of calculating the barrier height ΔUe enhanced by the MQB layer.

[Fig. 5]

A graph showing the result of calculating the degree to which a base transit time has been reduced in the HBT of the present invention having the barrier height enhanced by the MQB layer and

a graded composition base layer, compared with the base transit time in a conventional HBT having the uniform composition base layer.

[Fig. 6]

A graph showing the result of calculating the degree to which a maximum oscillation frequency f_{max} has been increased in the HBT of the present invention having the barrier height enhanced by the MQB layer and the graded composition base layer with an increased film thickness, compared with a conventional HBT having the graded composition base layer.

[Fig. 7]

A band diagram of the bipolar transistor of the present invention showing an improved temperature characteristic and a graph plotted as a function of temperature against a current amplification factor.

[Fig. 8]

A cross-sectional view of a conventional SiGe NPN heterojunction bipolar transistor using a graded composition base layer.

[Fig. 9]

A band diagram of a conventional SiGe NPN heterojunction bipolar transistor using a uniform composition base layer.

[Explanation of References]

1 Si substrate

2 Si subcollector layer

3 Si collector layer

4 SiGe base layer

5 Si emitter layer

6 Si emitter contact layer

10 MQB layer

10a well layer

10b barrier layer

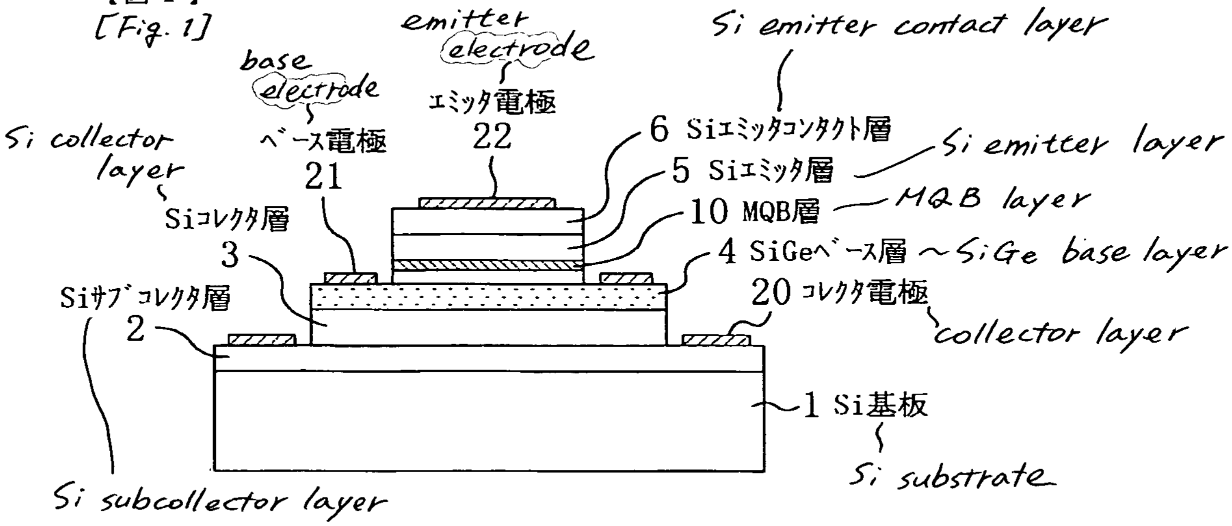
20 collector electrode

21 base electrode

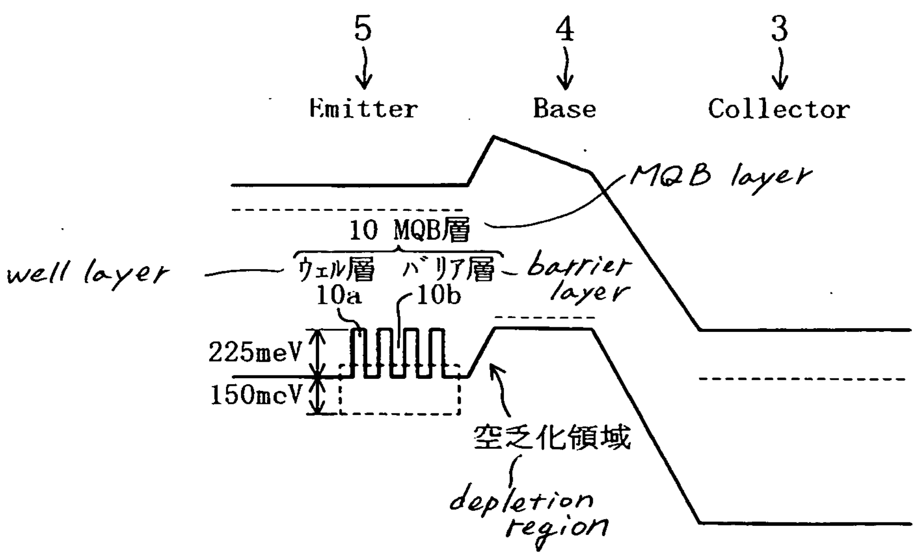
22 emitter electrode

【書類名】 図面
[Name of the Document] DRAWINGS

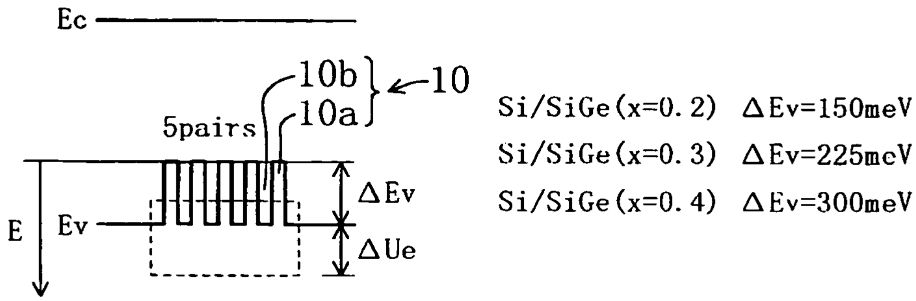
【図１】
[Fig. 1]



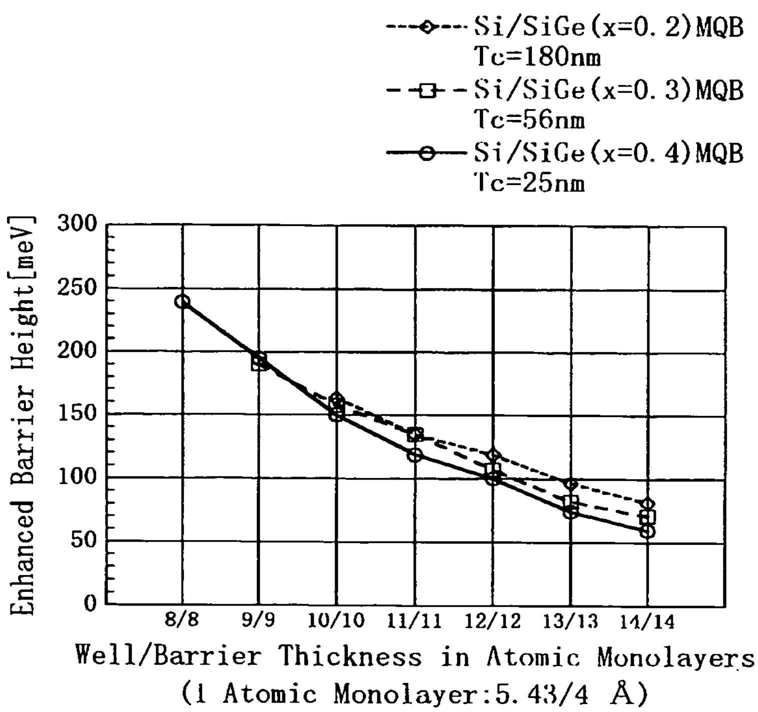
【図２】
[Fig. 2]



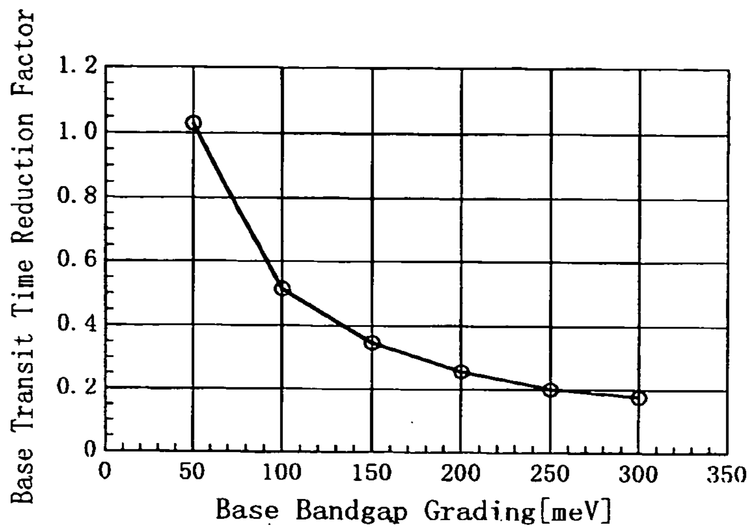
【図３】 [Fig.3]



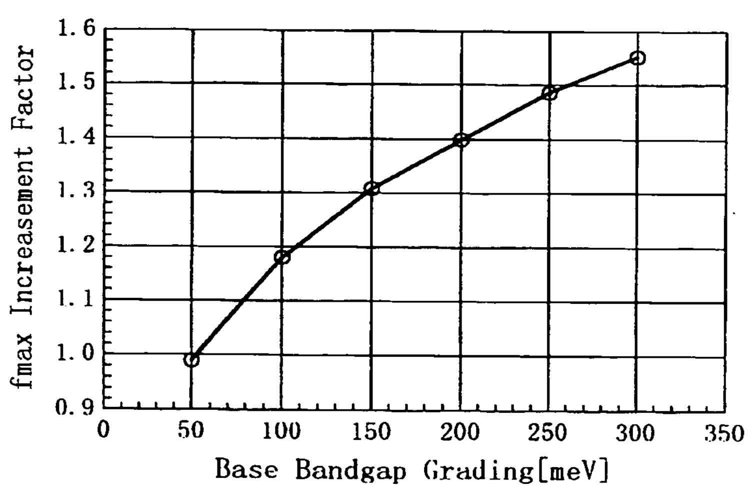
【図４】 [Fig.4]



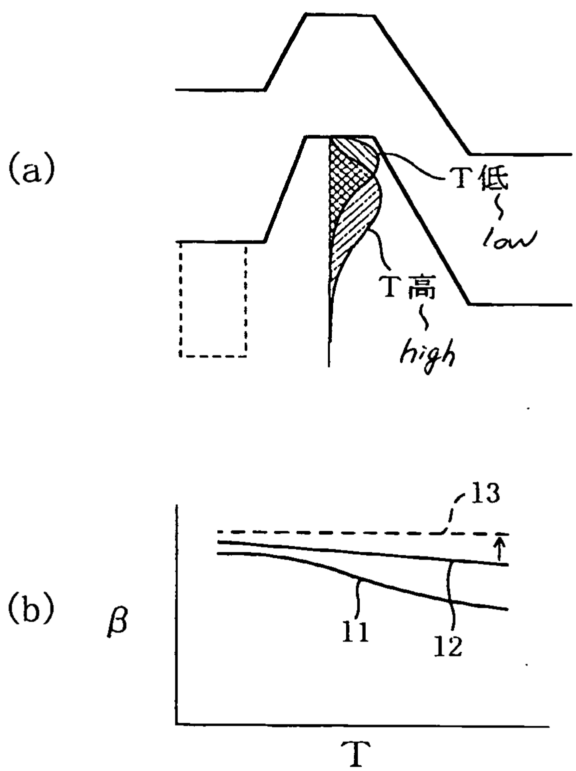
【図５】 [Fig. 5]



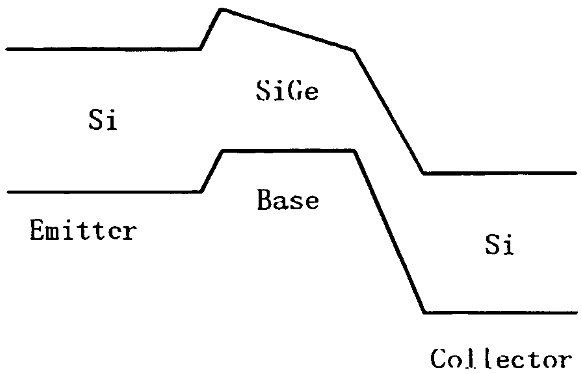
【図６】 [Fig. 6]



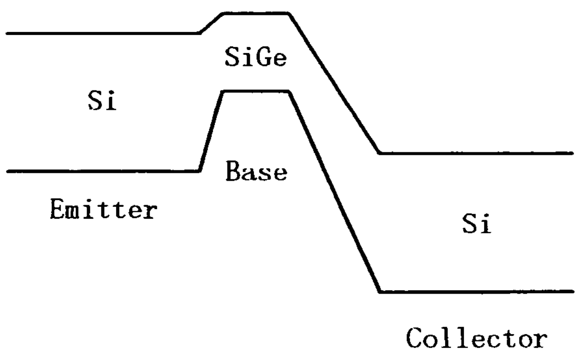
【図７】 [Fig. 7]



【図８】[Fig. 8]



【図９】[Fig. 9]



[Name of the Document] ABSTRACT

[Abstract]

[Purpose] To provide a bipolar transistor having excellent RF characteristics such as a current amplification factor, a current gain cutoff frequency and a maximum oscillation frequency in a microwave band or the like.

[Solution] In a region of a Si emitter layer 5 adjacent the base/emitter junction of a heterojunction bipolar transistor, a MQB layer 10 is provided as a multi-quantum barrier portion composed of a superlattice structure consisting of well layers 10a and barrier layers 10b that are formed of extremely thin films having different compositions and alternately stacked. This enhances an effective barrier height by using the effect of reflecting carriers and thereby suppresses reverse injection of the carriers from the SiGe base layer 4 into the Si emitter layer 5. As a result, the reverse injection of carriers is suppressed by the MQB layer 10 even when the base doping concentration is increased, which provides a satisfactory current amplification factor and increases a maximum oscillation frequency. In addition, even when a graded composition is given to the base layer to decrease the band discontinuity value at the emitter/base junction, a high maximum oscillation frequency can be obtained.

[Selected Figure] Figure 2